

RELATIONSHIP BETWEEN LIGHT INTENSITY AND VELOCITY OF AIR MOVEMENT
ON THE LEAF TEMPERATURES OF GREENHOUSE PLANTS

by

JAGDISH PRASAD NAUTIYAL

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Major Professor

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INTRODUCTION

The temperature of above ground parts of a plant are influenced by several environmental factors. Leaf temperatures govern the rates of numerous chemical and physical processes within the leaf, and these processes have optimum temperature requirements that control vital biological activities.

In direct sunlight, leaf temperatures are higher than the surrounding air temperatures. Leaves exposed to direct solar radiation usually have temperatures 2 to 10 degrees C higher than the surrounding air. The important factors influencing leaf temperatures are:

1. The supply of available moisture in the soil.
2. The evaporating power of the air.
3. Currents of air.
4. The intensity of light.
5. Solar and thermal radiation, air temperature, air movement and water loss or transpiration.

Light from the sun provides energy for green plants. If plants didn't perform the function of photosynthesis in changing radiant energy into chemical energy, this quantity of radiant energy from the sun would be converted directly into heat. The heat energy absorbed by the leaf is lost by conduction, transpiration and reradiation. In general, the greater the difference between the leaf temperature and the temperature of the surrounding air, the larger the heat loss by thermal emission.

Transpiration is important for keeping the temperature of the fully sunlit leaves below the lethal limit. A small quantity of water transpired

by leaves can mean a difference of a few degrees in plant temperatures. This can mean, under conditions of high temperature, the difference between survival and thermal death point (Gates, 15). The largest cooling from leaf transpiration takes place in still air or at very low wind speeds. Transpiration rates change with wind speed because of changes in the diffusion resistance of stomatas.

Within photosynthesizing cells the rate of carbon assimilation increases in a linear fashion with light intensity but at higher intensities the curve levels off. This indicates that at high light intensities light is wasted, the cells having become light saturated. At very high intensities assimilation diminishes, and leaves suffer from insolation. Insolation produces heat, causing increased leaf temperatures. High temperatures cause many different types of damage to plants, most evident is bleaching of chlorophyll from leaves, inhibition of growth, development of burns and lesions, or death of the plant or plant part.

Plants differ widely in the intensity of light that they require or tolerate. The compensation point is where rate of photosynthesis is equal to respiration rate. Similarly the light saturation point i.e. the point above which photosynthesis rate levels off or decreases. It is much lower for shade plants as compared to sun species. Under conditions of high light intensities all phases of growth are retarded and in extreme cases ultimate death of plants may occur. This all happens, partly due to high leaf temperatures, which disrupts the physiological processes.

Air cooling moderates high leaf temperatures by increasing their thermal emissivity. Cooling by heat transfer to the surrounding air is proportional to the difference between the leaf and air temperatures and

is a major factor in moderating the leaf temperature under high light intensities.

The purpose of this investigation was to study the effect of different rates of air movement on leaf temperature, stomatal opening and chlorophyll contents on the leaves of shade requiring plants under high light intensities. Further to explore the possibility of greater light intensity tolerance of these plants for commercial greenhouse production by modifying plant leaf temperatures through increased air flow.

REVIEW OF LITERATURE

Despite the fact that transpiration has been the subject of a great deal of study, there remains some uncertainty about the magnitude of its role in determining the temperature of the plant leaf. Clum (5) studied the effect of transpiration on leaf temperature and noticed that in general plants in dry soil with vasolined leaves were 2 to 4 degrees C warmer than the controls. In no case has a definite correlation been found between the transpiration rate and the difference between the leaf and air temperatures, nor between the difference of the transpiration rate of two leaves or plants and the difference of their temperature.

Clum (6) reported further that transpiration plays a small part in cooling the leaf, and suggested that radiation and convection from the leaf are more important than transpiration in keeping the leaf from becoming hotter than it does in bright sunlight. He observed that the thermal death point of plants lies between 45 and 55 degrees C, depending upon the nature of plant, condition within the plant, and the duration of the exposure. Convection is augmented by air currents and hence when air is moving those

leaves exposed are kept cooler more by convection and radiation than by transpiration. Intensity of light is the most important factor affecting the temperature.

Wolpert (41) showed, through a theoretical analysis, that under normal conditions transpiration could account for approximately $1/4$ of the heat removal from a leaf, indicating that transpiration was at least a significant factor in the heat exchange phenomena of leaves.

Cook et al (7), while working on transpiration, observed that transpiration appeared to establish a temperature variation over the area of the leaflet. Since the lowest temperatures are maintained near the leaf veins, they presumed this to be due to the greater transpiration. The transpiration component of heat exchange increased with increasing wind velocity up to 6 km/h, and as velocities rose beyond this value, transpiration became a decreasingly important factor in heat transfer. Light amplifies the part played by transpiration in heat transfer by causing stomatal opening, and in these tests accounted for leaf temperatures 5 degrees C lower than when transpiration was suppressed.

Gates (15) was of the opinion that transpiration is desperately important to a plant for keeping the temperature of the fully sunlit leaves below the lethal point. A small amount of transpiration can mean the difference of a few degrees in plant temperature which can under hot conditions mean the difference between the survival and thermal death. Transpiration cools the leaves and reduces the effective radiation load. The largest influence of transpiration on the leaf temperature takes place in still air and at very low wind speeds. This difference in transpiration is caused by wind speed because of changes in the diffusion resistance due to stomatal action.

Increase in wind velocity within limits results in an increase in the rate of transpiration. Winds of very high velocity have been observed to have a retarding effect upon transpiration due to closure of stomates. Wind may have a cooling effect upon the leaves, due to their thermal emissivity under intense insolation. Similarly large increases in photosynthesis can be obtained with air movement, probably reflecting the limitation of photosynthesis by air layering and the localized depletion of CO_2 at the actual surface of the leaf in still air. (Meyer and Anderson (28) and Leopold (22).)

Finell (13) summarized the effect of wind on plant growth as follows:

1. A portion of the tender foliage was actually destroyed by wind whipping.
2. Deformation of stem in early stages of growth.
3. Time of maturity was increased by wind, and yield of dry matter was reduced by 48 percent, but the number of secondary branches was apparently increased.

Martin and Clement (26) reported the transpiration of Helianthus annuus depended on the wind velocity. At velocities up to 2 mph the transpiration rate increases from the onset of wind and maintains this increase as long as wind continues. When the velocities are increased above this point, there is usually a high relative increase for the first few minutes, which in turn is followed by a decline. This causes slight wilting of leaves and closure of the stomata with a reduction in transpiration rates. The average increase of transpiration rate over a period of 2 to 4 hours rises very rapidly with velocities up to 2 to 3 mph, but the curves flatten out at this range and mount only gradually thereafter. He presented some evidence

which indicated that the closure of stomata by wind is partly mechanical and partly due to lowering the sap content of the leaves. Wind above 5 mph practically always induces closure of stomata and below 2 mph almost never. He found no difference in the mesophyll tissue, but found considerable drop in the xylem element area with increasing wind velocities.

Rao (29) investigated the effect of artificial wind on growth and transpiration in Italian millet and revealed that tips of plants subjected to wind were shorter, lighter in weight, thinner stalked and had narrower leaves and fewer tillers. These plants had lighter and less bulky root systems. The treated plants required double the amount of water as compared to non-treated plants.

Gessner (18) observed that the photosynthetic rate of plants with broad leaves was greatly enhanced by air turbulence, while in plants with finely divided leaves it was not appreciably increased.

Decker (11) found that the apparent photosynthetic rate of the entire shoot of tree seedling (loblolly pine) varies hyperbolically with the rate of air supply and linearly with mean CO_2 concentration over the range of 0.52 to 0.45 mg.

Went (35) has illustrated this by comparing photosynthetic rate of plants in still air and in an artificial wind. He obtained 20 percent increase in CO_2 fixation upon introducing turbulence and a prompt drop when the turbulence was withdrawn. Air layering around large flat leaves may be considerably more acute than around thinly divided leaves.

Wadsworth (32) devised some experiments to find the optimum wind speed for plant growth. He observed that the relative growth rate of Brassica napus in a wind tunnel rose with low wind speeds but fell again

when wind speed was further increased. A wind speed of 0.3 m/sec. caused optimal growth.

Wadsworth (33) conducted some experiments on the effect of artificial wind on the growth rate of plants in water culture. His experimental results showed no significant increase in relative growth rate or net assimilation rate with wind speed.

Wooley (41) explored the following three mechanisms by which wind might possibly increase transpiration. Increase in transpiration caused by decrease in air pressure on the side of leaf; ventilation of amphistomatous leaf by air passing through the leaf by way of stomatas and intercellular space and pumping action of changes in volume of intercellular space as leaves bend in air.

Raschka (30) remarked that a plant is never in thermodynamic equilibrium with its environment because the temperature of the sun is thousands of degrees higher than the temperature of the plant and energy is radiated to the plant and there transformed into heat. This process causes new gradients. Generally the temperature of part of the environment differs from that of the plant, causing a long wave radiation exchange. Also vapor pressure difference between them causes a long wave radiation exchange. Also vapor pressure difference between the plant and the environment creates a new gradient.

Whitehead (37) observed that the entire plant becomes smaller with increasing wind speed due to a smaller leaf area and not photosynthetic rates per unit area. Furthermore this reduction in leaf area is accomplished by a corresponding reduction of internode length. In general, the phenotypes become more xeromorphic as the wind speed is increased.

It has been demonstrated that these changes can be expected to be advantageous in respect to water relation.

Whitehead (38) studied the effect of wind on plant growth. He concluded that adaptative morphological and anatomical changes occur in both wind treated plants and those growing under soil moisture stress. These changes appear to be related to the conditions of water balance in the leaves. There is some evidence that photosynthetic apparatus itself is affected at the most extreme conditions.

Gates and Benedict (16) reported that all objects, including plants, when subjected to a heat load redistribute the absorbed heat in the form of reradiation, convection, conduction and transpiration. By these means the temperature of the plant remains within the lethal limits, unless the heat load becomes unusually heavy. The net energy retained by the leaf is utilized directly in photosynthesis, if the proper wave lengths are present. It also may be a means of increasing the chemical rate of processes within this food producing organ above that which could occur if the leaves were strictly at the ambient air temperature.

Gates et al (17) conducted some experiments on ponderosa pine. They determined the actual surface area of the branch, the effective area for absorbing long wave thermal radiation and for emission and the free and forced convection coefficient by suspending a solid silver casting of a ponderosa pine branch in an evacuated radiation chamber and in a wind tunnel. They concluded that the transfer of heat energy to and from ponderosa pine branch involves solar radiation, thermal radiation from the ground, atmosphere and surroundings, thermal emission by the branch and free convection in still air and forced convection in wind.

Miller and Saunder (27) conducted some experiments on the tempera-

ture of crop plants under field conditions during the summer. They observed that the transpiration rate of turgid leaves was much higher than that of wilted leaves. The temperature of turgid leaves was slightly below the temperature of surrounding air during early morning and evening. During night the temperature of leaves is approximately that of surrounding air and during day different plant leaves show different behavior. In direct sunlight the temperature of the base of the leaves is always lower than the tip. In diffused sunlight the temperature of attached, turgid leaves was always lower than that of surrounding air.

Curtis (8) found leaf temperatures to be considerably influenced by exchange of infrared radiation between the leaf and other materials near or at a distance from it. There is also loss of heat by radiation to space. He further concluded that rapid and great changes in temperature of leaves in direct sunlight are also brought about by natural or artificial changes in the rate of air flow or light intensity. The presence of water in the atmosphere either as vapor or clouds may influence plant temperatures through its effects on infrared radiation.

Lorenz (23) reported that according to Heilbrun and Miller the thermal death point for most plant cells has been found to vary between 45 to 55 degrees C. He reported that the following five theories explaining the mechanism of heat injury to protoplasm were found in the literature.

1. Coagulation-theory of protoplasmic proteins is probably the oldest and most widely accepted theory of heat injury. It was quoted by Sach as early as 1864.

2. Heat destruction of enzymes.
3. Asphyxiation theory.
4. Intoxication theory.
5. Lipoid liberation theory.

Waggoner and Shaw (34) observed that a leaf perpendicular to insolation was 3.2 degrees C warmer than a parallel leaf. Shaded leaves on all parts of the plant had nearly equal temperatures, while those exposed to insolation at the top of the plant and near the soil were 7.8 to 12 degrees C, respectively, warmer than shaded leaves. Upper exposed leaves were 3.3 to 8 degrees C warmer on clear days and 0.8 degrees C cooler on cloudy days than the air temperature.

Ansari et al (1) took the temperature readings of leaves of differing thicknesses under varying environmental and plant conditions during alternate heating and cooling cycles in sun and shade. They found that leaves tended to assume air temperature. Sunshine-heated thin leaves reached 6 to 10 degrees C above air temperature in one minute, and very thick leaves were heated 20 degrees C above air temperature in 20 to 30 minutes. Cooling in still air in shade was at the same rate as heating in sunshine. They further noticed that wind at 5 mph lowered leaf temperatures in the sun about half way to air temperature. This cooling effect can result in a reduction of transpiration by wind. Wilted leaves showed nearly the same temperature response as turgid ones. Dried leaves heated less and cooled faster in shade than transpiring leaves but showed similar heating and cooling curves.

The principle variable in the environment affecting photosynthesis is light intensity. The linear range of photosynthesis will proceed as

long as variables other than light are not critical. The saturation intensity is strongly influenced by the adaptation of the leaf, being lower for shade leaves than for sun leaves. Some investigators assert that intensities above 1000 ft-c are of no increased value to the plant since photosynthesis of individual leaves is saturated at that amount (Leopold, 22).

Boysen-Johnsen (4) demonstrated how adaptation of leaf to shade lowers the saturation intensity and usually shortens the linear range of photosynthesis.

Konis (20) was of the opinion that direct heat damage may be caused by high temperatures and thus there may also be indirect damage of high temperatures resulting from an undesirable effect on physiological processes as photosynthesis and transpiration. Damage may also be due to a low photosynthesis-respiration ratio. He also pointed out that plasma hydration is most likely the cause of resistance in plants.

Böhming (2) described the decline in photosynthesis when continuous light was applied to apple leaves and showed that leaves which have been adapted to full sunlight are much more resistant to continuous light than shade leaves.

Withrow and Withrow (36) showed that in some species continuous light results in extreme chlorosis of the leaves, a situation that can be avoided either by a daily dark period or by daily temperature fluctuations.

Böhning and Burnside (3) measured rate of apparent photosynthesis in relation to light intensity in leaves of several species of plants exposed to similar conditions of light, temperature, moisture and CO₂ supply. Light saturation curves for apparent photosynthesis of 8 sun species and

5 shade species were drawn and it was noticed that the light saturation and compensation point for sun species were 2000 to 2500 ft-c. and 100 to 150 ft-c., respectively. They found that for shade species light saturation was reached at a maximum of 1000 ft-c. and in some shade species light saturation intensities were as low as 400 to 500 ft-c. The compensation points of the shade species were approximately 50 ft-c.

Georg (19) found that the relation between stomatal transpiration in wind and still air (10 different species) varies between 1:3 and 1:9.

Kuiper (21) while working on the effect of environmental factors on the transpiration of leaves, with special reference to stomatal light response, reported that the transpiration rate showed a linear increase with light intensity, which was mainly due to increase in leaf temperature by irradiation with incandescent light. With other light sources, containing a low amount of infrared irradiation, the increase in transpiration was mainly due to an increase in stomatal openings. The stomates were found to be insensitive to infrared radiation.

Emerson (12) showed that the maximum rate of photosynthesis is a smooth function of the chlorophyll content.

Lubimenko and Hubbenet (24) worked on the influence of temperature on the rate of accumulation of chlorophyll in etiolated seedlings and reached the following conclusions:

1. The greening process of etiolated wheat seedlings takes place within definite limits of temperature, beginning between 2 and 4 degrees C; attaining its maximum rate between 26 and 30 degrees C, and ceasing at a temperature near 48 degrees C.
2. The position of these cardinal points does not depend upon

the duration of the seedlings' exposure to light.

3. The optimal temperature point is characterised by the accumulation of a maximal quantity of chlorophyll in the shortest time.
4. This relation of greening process to temperature rests on the influence of this factor on the synthesis of leucophyll and on its transformation into chlorophyllogen, since the transformation of chlorophyllogen into chlorophyll is a purely photochemical reaction not depending upon temperature.
5. In the temperature interval from 2 to 30 degrees C the increase in the quantity of chlorophyll in a unit of time, first grows and then falls with the length of time the seedlings are exposed to light at the same temperature.
6. The increase in the production of chlorophyll during the first period of exposure to light is conditioned by the secondary influence of light on the reactions of chlorophyllogen formation, as these reactions are endothermic. The absorption of light by the greening plastids augments the quantity of energy and in this way helps the acceleration of the reaction.
7. The fall in production of chlorophyll in a unit of time begins from the moment when the quantity of an accumulated pigment attains approximately 40 percent of its limit quantity, independent of temperature. That is why the more rapid the accumulation, the earlier the fall in the rate of production will appear.
8. At temperatures higher than 30 degrees C, a general fall can

be observed in the production of chlorophyll, the quantity being smaller than that produced at the optimal temperature.

9. The diminution of total chlorophyll production at temperatures higher than 30 degrees C, is probably conditioned by the appearance of a new reaction under its influence obtained from leucophyll, instead of chlorophyllogen already formed and decomposed.
10. The new reaction which diminishes the production of chlorophyll begins at temperatures near 26 degrees C, as the temperature rises its rate increases and at maximal temperature becomes equal to the rate of the chlorophyllogen synthesis. The production of this pigment and with it that of chlorophyll, then falls gradually to zero.

Fleischer (14), while working on the relation between chlorophyll content and the rate of photosynthesis, concluded that the rate of photosynthesis is proportional to the chlorophyll content when the latter is varied by varying the iron supply. These data give a straight line passing through the origin, which is not true of Emerson's result.

Sironval and Kandler (31) reported that the process of pigment bleaching in *Chlorella* cells exposed to very intense light (10,000 lux) consisted of two phases--an induction phase preceding bleaching and a bleaching phase. Both phases required oxygen. During the bleaching phase carotene disappeared, then chlorophyll a, chlorophyll b and finally carotenoids. The induction of bleaching in dark was reversible and seemed to reflect important changes in cell metabolism.

Walker and Mellon (39) conducted some experiments on bleaching of chloroplastin and were of the opinion that chloroplast could be bleached by heat, light or a combination of both. They further reported that the rate of bleaching of chloroplastin was independent of temperature in light. The rate of bleaching in darkness became temperature dependent above 30 degrees C.

MATERIALS AND METHODS

Five species of commonly grown shade plants were selected for this investigation. These species were:

1. Saintpaulia ionantha.
2. Philodendron cordatum,
3. Begonia semperflorens,
4. Codiseum auculifolium, and
5. Sansevieria trifasciata.

Pot grown plants of each species were grown in a greenhouse at light intensities of 1500 to 2000 ft-c. for two months prior to initiating the study.

Five plants of each species were selected and double potted into eight-inch clay pots. The space between the two pots was filled with peat moss to avoid rapid evaporation of moisture from the clay pot surface.

A horizontal funnel-shaped wind tunnel twenty feet long facing east-west was set up in a greenhouse to create controlled wind velocities (Plate I). The tunnel consisted of a plastic sheet supported on a wooden frame. The narrower end of this funnel-shaped tunnel was two feet square and the broader end eight feet square. An exhaust fan was installed at

EXPLANATION OF PLATE I

Section of horizontal, plastic covered wind tunnel
showing the fan end and wooden shelf to support plants.



PLATE I

the narrower end and aspen-wood-excelsior padding with facilities for wetting was mounted at the wider end. The wet padding was used for humidification and cooling of the air entering the chamber. A horizontal wooden board was placed along the length of the tunnel to support plants in the center of the chamber (Plates I and II). Wind velocities in the tunnel were measured by means of an omnidirectional air meter and they varied from 0.45 mph at the wider end to 5 mph at the narrower end. Four spots for placing plants were marked on the horizontal wooden board in the tunnel to receive wind velocities of 4.4, 3.2, 0.6 and 0.45 mph, respectively.

This study was conducted in a plastic greenhouse at Kansas State University during the months of July and August, 1965. Philodendron cordatum plants were put under experimentation on 1st July, Sansevieria trifasciata on 10th July, Codiaeum variegatum and Begonia semperflorens on 15th July and Saintpaulia ionantha on 20th July, 1965.

One plant of each species was placed on the wooden board at a distance of five feet from one another where the wind speeds were 4.4, 3.2, 0.6 and 0.45 mph, respectively, and one plant was placed outside the wind tunnel to serve as a control. The fan operated daily from 7:30 a.m. to 5:00 p.m.

The temperatures of two leaves selected at random from each plant were taken by inserting standardized 36 gauge copper-constantan thermocouples into their midribs. The junctions of the thermocouple were made by twisting the copper and constantan wire and then fusing the joint. This joint was raked with a file so as to make it pointed in order to facilitate insertion in the leaves.

EXPLANATION OF PLATE II

View of horizontal plastic covered wind tunnel showing it lengthwise from pad covered air intake (background) to fan end for air exhaust.



PLATE II

The temperature readings of the leaves and air were taken with a portable potentiometer (Rubicon Co.) calibrated in Fahrenheit scale (Plate III). Air temperatures were measured by holding the thermocouple in the shade. Air and leaf temperatures were taken weekly on clear days at 9:00 a.m., noon and 4:00 p.m.

Light intensities were measured weekly in conjunction with temperature readings using a Weston illumination meter (Model 756). Plant heights were also measured weekly to determine the linear growth rate. Observation notes on general appearance and growth of the plants were taken. Opening and closing of stomates in different wind velocities and in still air were also observed from time to time under a binocular microscope.

Leaf samples from Saintpaulia ionantha were analyzed for chlorophyll content after 30 days of treatment and similarly leaves from other species were analyzed after 45 days. All the leaves of the plants at the different wind velocities and control were chopped after removing their midribs. Random samples from chopped leaves of the plants were taken for chlorophyll analysis (Mackinney, 25). Each sample consisted of 0.5 g of cut-up leaf tissue, a pinch of sand and a few ml of 80 percent acetone. These were placed in a mortar and ground with a pestle. The supernatant liquid was decanted and filtered. Eighty percent acetone was added to the residue and ground again before filtering. This was repeated until the filtrate was colorless and then diluted to 50 cc with 80 percent acetone.

Using 80 percent acetone as the blank, the optical density (absorbance) of the sample was measured on the Beckman DU Spectrophotometer at 663 m μ and 645 m μ and compared with 80 percent acetone as a blank. The concentrations of chlorophyll a and chlorophyll b were found by solving

EXPLANATION OF PLATE III

Potentiometer with one end of the thermocouple
inserted in the midrib of a Philodendron cordatum leaf.



PLATE III

the following linear equation:

$$\text{optical density } 663 \text{ m}\mu = 82.04 C_a + 9.27 C_b$$

$$\text{optical density } 645 \text{ m}\mu = 16.75 C_a + 45.6 C_b$$

if C = the concentration in grams per liter and

$10 C$ = the grams of chlorophyll a or b per 100 g of leaves,

then the total chlorophyll content in grams per 100 g of leaves

$$= 10 C_a + 10 C_b .$$

EXPERIMENTAL RESULTS

Visual Symptoms

Philodendron cordatum

The first sign of injury occurred on control plants outside the chamber. Yellow spots were observed on three leaves of philodendron after a period of seven days. The yellow spots grew in dimension and the number of leaves showing this chlorosis increased during the 45 days of the study. After fifteen days, burning of the margin of young leaves was noticed. At the end of the study enlarged burned spots were noticed on nine leaves and bleaching effects were seen on most of the leaves. The plant had 29 leaves.

Plants at the wind velocity of 4.4 mph appeared normal with burned spots on one leaf with slight yellow discoloration. The plant at 3.2 mph wind velocity differed from that at 4.4 mph in having more yellowish discoloration. At 0.6 mph wind velocity yellowish discoloration on plants was noticed after fifteen days and at the end of the experiment more leaves had a yellowish appearance when compared to plants at 4.4 and 3.2 mph velocities. At 0.45 mph velocity plants were like that of 0.6 mph with exception of burned spots. The relative degree of discoloration and burning acquired by plants at different wind velocities is shown in Plate IV.

No appreciable difference in rate of growth was found between plants at 4.4 and 3.2 mph velocities. The rate of growth of plants at control conditions was less than that at 4.4 and 3.2 mph wind velocities (Table 1). The size of leaf at 4.4 and 3.2 mph air flow was larger than that of control (Plate IV).

EXPLANATION OF PLATE IV

Difference in Philodendron cordatum leaf size and injury as related to velocity of air movement.

Top Row (L to R) - Leaves at control, 0.45 mph and at 0.6 mph wind velocities.

Bottom Row (L to R) - Leaves from plants at 3.2 mph and 4.4 mph wind velocities.

PLATE IV



Sansevieria trifasciata

All sansevieria plants were normal for the first fifteen days and thereafter the plant at 0.45 mph wind velocity and the control started showing signs of faded green chlorosis. After 45 days of study the control showed much more green discoloration compared to plants at 0.6 and 0.45 mph velocities. The plant at 0.45 mph velocity also showed a large sunburned spot on one leaf (Plate V). Plants at 4.4 mph wind velocity had more chlorotic appearances than those of plants at 3.2 and 0.6 mph wind velocities.

Growth of plants at 4.4, 3.2 and 0.6 mph wind velocities did not show any difference in plant height. But the plant at 0.45 mph wind velocity did show the best growth in spite of one burned spot. The plant at control lagged behind and was poorest among all plants (Table 2).

Codiaeum auculifolium

Leaves of the codiaeum plant outside the chamber became orange-yellow in color with slight burning of the three young leaves fifteen days after exposure to full sunlight. The plants at 4.4 and 3.2 mph wind velocities in the chamber at the same light intensities were green but looked stunted in growth, whereas the plants at 0.6 looked normal and healthy with slight burning of two leaf margins. The plant at 0.45 mph wind velocity looked healthiest with three more secondary branches. The control plant outside the chamber showed signs of burning injury on the margin of six young leaves. At the end of 45 days the plants at 4.4 and 3.2 mph wind velocities were normal green but stunted in growth, whereas the plant at 0.45 mph wind velocity was very healthy with secondary branches. The plant

EXPLANATION OF PLATE V

Amount of heat injury caused by high light intensity to
Sansevieria trifasciata at different velocities of air movement.

L to R - Leaves from plants at 4.4 mph, 3.2, 0.6, 0.45 mph wind
velocities and at control.



Table 1. Philodendron cordatum, plant growth in relation to plant height.

Days after treatment	Wind velocity in mph				
	0.0	0.45	0.6	3.2	4.4
	Plant height in cm				
7	6.3	5.0	5.3	6.2	6.1
14	13.0	11.3	12.5	13.3	13.2
21	19.7	17.3	18.7	20.7	21.0
28	27.7	23.0	24.0	28.7	29.0
35	29.7	25.3	25.5	30.5	31.2
42	32.5	27.4	27.1	34.2	34.0
45	35.2	29.3	28.7	38.3	38.0

Table 2. Sansevieria trifasciata, plant growth in relation to plant height.

Days after treatment	Wind velocity in mph				
	0.0	0.45	0.6	3.2	4.4
	Plant height in cm				
7	3.1	2.8	2.7	3.0	2.9
14	6.7	5.11	5.4	6.2	5.8
21	9.2	9.0	8.6	8.11	8.4
28	11.1	12.9	12.1	12.5	11.1
35	13.6	15.7	14.7	15.4	13.3
42	14.1	18.4	16.2	17.1	15.7
45	15.0	20.1	17.1	18.5	17.3

outside the chamber showed better growth and had more secondary branches than the plants at 4.4 and 3.2 mph wind velocities (Table 3). The plant growth in relation to height decreased with increase in wind velocity. The plant outside the chamber was tanned with yellow pigmentation with nine leaf margins which were observed burned whereas the plants at 4.4 and 3.2 mph wind velocities showed only slight yellow discoloration (Plate VI).

Begonia semperflorans

No visible signs of leaf injury were noticed during the first seven days, but after fifteen days signs of minor burns were noticed on two leaves of the control plant. After three weeks the plant at 4.4 mph velocity showed a sunburned spot on one of its leaves and the plant was stunted in growth; with the exception of two sunburned injured leaves, the plant at 3.2 mph velocity was similar in appearance to the plant at 4.4 mph wind velocity. These plants had 27 and 29 leaves, respectively. Plants at 0.6 and 0.45 mph velocities each showed sunburn spots on four leaves out of 38 and 47 leaves, respectively, but otherwise they were healthy with more secondary branches. The plant under control showed bronze colored pigmentation with signs of burn injury on six out of 50 leaves (Plate VII).

In regard to growth in relation to height, the plant at 0.45 mph wind velocity was healthiest and had the most secondary branches. Plants at 4.4 and 3.2 mph velocities were stunted in growth (Table 4). The plant growth, in relation to height, decreased with increase in wind velocity.

Table 3. Codiaeum auculifolium, plant growth in relation to plant height.

Days after treatment	Wind velocity in mph				
	0.0	0.45	0.6	3.2	4.4
	Plant height in cm				
7	2.0	3.7	3.7	2.8	3.3
14	3.0	5.5	5.7	4.3	5.5
21	5.3	8.7	7.7	8.3	9.3
28	6.7	11.3	8.4	11.0	12.0
35	11.6	15.0	9.8	12.8	12.6
42	16.5	19.7	13.2	13.7	13.3
45	17.6	21.2	15.1	14.3	13.5

Table 4. Pegonia semperflorens, plant growth in relation to plant height.

Days after treatment	Wind velocity in mph				
	0.0	0.45	0.6	3.2	4.4
	Plant height in cm				
7	1.0	0.7	1.3	1.2	1.8
14	3.2	2.7	2.8	3.2	4.0
21	4.3	4.0	3.7	4.0	4.5
28	4.9	5.8	4.7	4.5	4.9
35	5.2	7.8	5.2	4.9	6.0
42	7.5	9.7	7.6	6.2	6.6
45	10.2	12.0	10.4	7.6	7.4

EXPLANATION OF PLATE VI

Differences in leaf size, yellow pigment formation and leaf injury resulting from different velocities of air movement to Codiaeum auculifolium.

Top Row - (L to R) - Leaves from plants at control, 0.45 mph and 0.6 mph wind velocities.

Bottom Row - (L to R) - Leaves from plants at 4.4 and 3.2 mph wind velocities.

PLATE VI



EXPLANATION OF PLATE VII

Amount of injury to Begonia semperflorens plants kept
at different wind velocities.

Top Row (L to R) - Leaves from plants at control, 0.45 mph
and 0.6 mph wind velocities.

Bottom Row (L to R) - Leaves from plants at 4.4 mph and 3.2 mph
wind velocities.



PLATE VII

Saintpaulia ionantha

Compared with other species the saintpaulia plants showed maximum amount of heat injury. After seven days from the initiation of the study, plants at 3.2, 0.6, and 0.45 mph wind velocities and the control started to show yellowish leaf discoloration. These signs of bleaching became quite prominent after fifteen days. The control plant showed maximum number of leaves sunburned along with the yellowish discoloration. After a 30 day period it was observed that the plant least affected by heat injury was at 4.4 mph wind velocity as only three leaves had slight burning of leaf margins and bleaching effect on seven leaves out of a total of 25 leaves. At 3.2 mph wind velocity burning of leaf margins was noticed on four leaves and bleaching on 10 leaves out of a total of 28 leaves. The most affected was the control as enlarged burned spots were observed on 11 leaves and bleaching on almost all leaves. Heat injury increased with decrease in wind velocity (Plate VIII).

The rate of growth as judged by general appearance was directly proportional to wind velocity. Plants at 4.4 and 3.2 mph velocity made new growth, whereas the control plant first made some growth but later was slightly damaged by high light intensity and thereafter the plant did not make any growth. Leaf size at 4.4 and 3.2 mph wind velocities was larger than that of the control plant (Plate VIII).

Leaf Temperatures

Leaf temperatures as measured with thermocouples at 9 a.m., noon and 4 p.m., showed the following trends at various wind velocities and control (Table 5). Leaf temperatures increased with decreasing wind velocities.

EXPLANATION OF PLATE VIII

The amount of burning and chlorosis caused to leaves of Saintpaulia ionantha grown under different wind velocities.

Top Row (L to R) - Leaves from plants at control, 0.45 mph and 0.6 mph wind velocities.

Bottom Row (L to R) - Leaves from plants at 4.4 mph and 3.2 mph wind velocities.



PLATE VIII

Among control plants maximum temperature at noon was attained by Sansevieria trifasciata leaves that were 10.2 degrees F above air temperature; Philodendron cordatum 7.2 degrees F above air temperature; Codiaeum auculifolium 6.4 degrees F above air temperature, Saintpaulia ionantha 9.4 degrees F and Pegonia semperflorens 7 degrees F above air temperature at 6685 ft.-c. light intensity. Lowest leaf temperatures were observed at noon in all plants kept at 4.4 mph wind velocity. Compared to other treatments leaf temperature of Sansevieria trifasciata was 2 degrees F above air temperature, Philodendron cordatum was 1.5 degrees F, Saintpaulia ionantha 1.9 degrees F, and Pegonia semperflorens 1.1 degrees F above air temperature (Table 5).

In general leaf temperatures increased with increase in light intensity. Differences between leaf and air temperatures were 3 to 5 degrees F occurring in morning and evening (Tables 5 and 6).

The average light intensity during the experimental duration was 2270 ft.-c., 6685 ft.-c. and 3045 ft.-c. for the morning, noon and evening, respectively (Table 7).

Stomatal Observation

It was observed that the stomates remained open in still air and at 0.6 and 0.45 mph wind velocities. At 4.4 and 3.2 mph wind velocities stomates tended to close after 15 minutes on the onset of wind and remained in that position throughout the period of air flow. The stomates of all plants under control during this comparison remained wide open.

Table 5. Leaf temperatures at several wind velocities for different plant species with accompanying air temperatures in degrees F at 9 a.m.

Plant species	Wind velocity in mph				Wind velocity in mph			
	4.4	3.3	0.6	0.45	0.0	4.4	3.2	0.6
	Leaf temperature of					Air temperature °F		
<u>Philodendron cordatum</u>	84.0	84.5	85.0	84.2	90.5	84.2	83.3	83.0
<u>Sansevieria trifasciata</u>	84.5	85.0	86.0	84.7	91.6	"	"	"
<u>Codiaeum auculifolium</u>	84.0	84.7	85.1	84.3	90.1	"	"	"
<u>Saintpaulia ionantha</u>	84.7	85.2	86.2	85.0	92.1	"	"	"
<u>Pegonia semperflorens</u>	84.3	85.0	85.5	84.3	91.0	"	"	"

Table 6. Leaf temperatures at several wind velocities for different plant species with accompanying air temperatures in degrees F at noon and evening.

Plant species	Wind velocity in mph					Wind velocity in mph				
	4.4	3.3	0.6	0.45	0.0	4.4	3.2	0.6	0.45	0.0
	Leaf temperature °F					Air temperature °F				
						Noon				
<u>Philodendron cordatum</u>	91.0	91.8	93.1	93.4	101.4	89.3	90.0	91.0	90.0	94.2
<u>Sansevieria trifasciata</u>	91.7	93.4	93.8	93.8	104.4	"	"	"	"	"
<u>Codiaeum auculifolium</u>	90.6	91.6	92.4	92.4	100.6	"	"	"	"	"
<u>Saintpaulia ionantha</u>	91.6	92.6	93.8	94.1	103.6	"	"	"	"	"
<u>Begonia semperflorens</u>	90.7	91.7	92.8	92.6	101.2	"	"	"	"	"
						Evening (4 p.m.)				
<u>Philodendron cordatum</u>	87.2	88.3	89.5	90.0	93.9	86.3	86.8	87.7	87.9	89.8
<u>Sansevieria trifasciata</u>	87.9	89.0	90.6	90.7	94.7	"	"	"	"	"
<u>Codiaeum auculifolium</u>	86.7	87.8	89.3	89.6	93.1	"	"	"	"	"
<u>Saintpaulia ionantha</u>	87.2	88.5	90.4	90.6	94.6	"	"	"	"	"
<u>Begonia semperflorens</u>	87.0	87.8	89.4	89.3	93.3	"	"	"	"	"

Table 7. Light intensities in foot candles (ft-c.) at 9 a.m., noon and 4 p.m.

Date (1965)	Light intensity in ft-c.		
	9 a.m.	Noon	4 p.m.
3rd July	2010	6768	1140*
10th July	1998	6678	2892
17th July	2074	6774	3008
24th July	2440	6560	3028
31st July	2450	6772	2940
7th August	2210	6660	3090
14th August	2236	6404	3100
21st August	2382	6774	3060
28th August	2342	6844	3238
Average	2270	6685	3045

*This light intensity was recorded at 5 p.m., otherwise all intensities were taken at 4 p.m.

Chlorophyll Content

The quantitative estimation of chlorophyll contents of Philodendron cordatum and Saintpaulia ionantha leaves showed a decrease at slower wind velocities. Maximum chlorophyll destruction and reduced synthesis were found in control plants. On the other hand, chlorophyll content was found to be less with increased wind velocities for Codiaeum auculifolium and Begonia semperflorens. In Sansevieria trifasciata maximum loss of chlorophyll was found in control plants and was highest at 0.45 mph and decreased with increases in wind velocity (Table 8).

Table 8. Chlorophyll content in grams per 100 grams fresh weight.

Plant species	Treatment				
	Wind velocity mph				
	4.4	3.2	0.6	0.45	0.0
<u>Saintpaulia ionantha</u>	.016	.014	.011	.010	.007
<u>Philodendron cordatum</u>	.058	.049	.030	.035	.028
<u>Codiaeum auculifolium</u>	.038	.046	.040	.057	.049
<u>Begonia semperflorens</u>	.006	.010	.009	.011	.015
<u>Sansevieria trifasciata</u>	.027	.034	.032	.038	.017

DISCUSSION

Light intensity is the major environmental factor affecting plant temperature and photosynthesis. The saturation intensity is strongly influenced by the adaptation of the species, being much lower for plants which are adapted to shade conditions. According to Leopold (22), and Böhning and Burnside (3), all phases of growth of typical shade species are usually retarded by light intensity in excess of about 1000 ft-c. When light intensity exceeds this limit many injuries result from solarisation due to excessive heat load.

The results obtained in this study showed that leaf temperatures tend to rise with an increase in light intensity. The maximum leaf temperatures were observed at noon when light intensity averaged 6685 ft-c. (Table 7). The higher leaf temperatures were observed in all species and under all treatments (Table 6). Leaves of control plants (normal greenhouse air movement) reached the maximum rise in temperature, in this study, 6.5 to 10.2 degrees F above air temperature. Similar results have been reported by Ansari et al (1), Cook et al (7), Clum (6) and Waggoner and Shaw (35) who found that leaf temperature of sunlit leaves were always higher than the air temperature. Furthermore, under no condition was the temperature of sunlit leaves found to be lower than the air temperature, as reported by Miller and Saunder (27). The leaf temperatures of all plants in the morning, noon and evening either under forced air movement or control, were always higher than the air temperature, although the differences varied with light intensity (Tables 5 and 6).

Wind modifies elevated leaf temperatures. Plants at 4.4 and 3.2 mph wind velocities were found to have leaf temperatures of 1 to 3.5 degrees F

above air temperature and these differences tended to increase with decrease in air flow (Table 6). The effect of wind was found to be more pronounced in the morning and evening when the temperature of leaves at 4.4 and 3.2 mph wind velocities tended to approach the air temperatures (Table 5 and 6). Perhaps, wind modifies leaf temperatures by lowering the air temperature surrounding the plants and thus reducing the temperature gradient of leaves by reradiating the absorbed heat to the surrounding atmosphere. Air flow also dissipates the moist vapor blanket surrounding the leaves increasing the rate of transpiration. All these factors give the cumulative effect of forced convection. At 4.4 and 3.2 mph air velocities, the reduction in leaf temperatures was perhaps mainly due to the cooling effect of air, since transpiration was inadequate to account for this and the cooling based upon differences of air and leaf temperature must become dominant. These findings are supported by Ansari et al (1), Curtis (8), Gates (17), Martin and Clements (26) who have found that convection augmented by air currents and reradiation are more important factors in cooling leaves than transpiration.

The temperature of plant leaves under normal greenhouse air movement, where transpiration due to stomatal opening was the major factor in lowering the leaf temperature, rises from 6.5 to 10.2 degrees F above air temperature (Table 6). Hence, the cooling effect by transpiration was not so effective as by forced convection at 4.4 and 3.2 mph air velocities. This fully agrees with the findings of Clum (5 and 6), Wolpert (41), Cook et al (7) who are of the opinion that transpiration can only reduce elevated leaf temperatures from 3 to 5 degrees C.

The stomates of leaves in all plants at 4.4 and 3.2 mph air velocities were observed to be closed and this further strengthens the view that under these conditions forced convection is the major factor in reducing the leaf temperatures, since transpiration mainly occurs through stomates. The closing of stomates here by wind is partly mechanical and also due to lowering the fluid contents of cells. This condition may be beneficial to plants in relation to water conservation. Martin and Clements (26) also noticed this kind of behavior by stomates.

The stomates of leaves at 0.6 and 0.45 mph wind velocities remained open and hence here the reduction in leaf temperature was by both transpiration and air flow. The temperature of these leaves were found to be 4 to 5 degrees F above air temperature, which is less than the temperature of control leaves, but more than the temperature of leaves at 4.4 and 3.2 mph wind velocities (Table 6). Gates (14 and 15), Wolpert (40) are also of the opinion that the greatest effect of transpiration on leaf temperature is when air is still or at low wind speeds. According to Georg (19), and Kiuper (20), transpiration is more efficient in still air than in wind.

Leaves of different species showed different trends in temperature under similar treatments. Thick leaves of Saintpaulia ionantha and Sansevieria trifasciata had a higher temperature than thin leaves of Philodendron cordatum, Codiaeum auculifolium and Begonia semperflorens (Table 6). Similar results were reported by Ansari et al (1) and Leopold (22).

Perhaps leaves with rough surfaces acted as heat traps when compared to leaves with shiny surfaces which have reflectance properties. The pubescent leaves of Saintpaulia ionantha were 3 degrees F higher than the glossy Codiaeum auculifolium leaves under the control conditions in this study (Table 6).

Shade plants may cease growth when temperatures rise to 40 degrees C (104 degrees F), but death occurs only if plant temperatures rise higher. This is time dependent. The temperature of leaves of all plants of different species under the control conditions ranged from 101.2 degrees F to 104.5 degrees F during the period of high light intensity (Table 6) and hence this prolonged exposure to high temperature was associated with the maximum amount of chlorosis and burning lesions. The degree of damage depended upon the leaf temperature, as Saintpaulia ionantha had much more leaf damage (Plate VIII) than those of Philodendron cordatum (Plate IV) or Codiaeum auculifolium (Plate VI). Plants exposed to air flows of 4.4 and 3.2 mph showed a minimum amount of injury symptoms because here the leaf temperatures ranged from 90 to 93 degrees F. Similarly at 0.6 and 0.45 mph wind velocities these symptoms of injury were more extreme than at higher wind velocities, but less than the control (Plates IV to VIII). These signs of bleaching are probably due to denaturation of proteins. Photo-oxidation of chlorophyll and death of tissue can occur due to coagulation of protoplasm. The degree of damage varied with species and temperature of the leaves. Similar results have been reported by Konis (21), Lorens (23) and Withrow and Withrow (37).

Chlorosis or bleaching of leaves is mainly due to the destruction of the photosynthetic apparatus in chlorophyll. The amount of such damage varied with rate of air flow and species (Plates IV to VIII). This destruction of chlorophyll is due to photo-oxidation which is the result of high light intensity and high temperature. Sironval and Kandler (32) and Walker and Mellon (40) also found this kind of effect with high light intensity and temperature.

Lubimenko and Hubbenet (24) found that at temperatures above 30 degrees C a general reduction in rate of chlorophyll synthesis occurs and this continues with increase in temperature. At considerably higher temperatures synthesis stops. The quantitative analysis of chlorophyll in leaves of Saintpaulia ionantha and Philodendron cordatum showed that it increased with increased wind velocity (Table 8). This was probably due to the lower temperatures of leaves at wind velocities of 4.4 and 3.2 mph as compared to that of control where maximum destruction to chlorophyll occurred. On the other hand leaves of Codiaeum auculifolium, Begonia semperflorens and Sansevieria trifasciata showed a different trend in chlorophyll content (Table 8). Loss was greater in plants exposed to 4.4 mph air velocity as compared to those at 0.45 mph wind velocity where the temperature ranged from 92.5 to 94.5 degrees F. This unusual trend of these species might be due to a combination of factors of high humidity at 0.45 mph and high light intensity tolerance adaptation by the species. These species have pigmented leaves and the pigmentation increased with decreased air flow, especially with Codiaeum auculifolium (Plate VI) and Begonia semperflorens (Plate VII). It is also possible that the pigmentation reduced or filtered the high light intensity thus preventing chlorophyll destruction or increasing its synthesis.

The rate of growth in respect to plant height showed a decrease with increase in wind velocity especially with Sansevieria trifasciata (Table 2), Begonia semperflorens (Table 4) and Codiaeum auculifolium (Table 3). Similar results have been reported by Rao (29) and Whitehead (38).

It has been found that the growth and general appearance were directly related to the amount of chlorophyll present in Begonia semperflorens

(Table 4), Sansevieria trifasciata (Table 2) and Codiseum auculifolium (Table 3). Best growth was observed in plants at 0.45 mph wind velocity where chlorophyll content was also highest (Table 8). Similarly in Saintpaulia ionantha (Plate VIII) and Philodendron cordatum (Plate IV and Table 1) growth was best, as measured by plant height and leaf size, at 4.4 and 3.2 mph air velocities where the chlorophyll contents were also highest (Table 8). At normal greenhouse air movement the growth rate declined proportionally to the reduction of chlorophyll. These results support the view of Emerson (12) who found that the rate of photosynthesis is a smooth function of chlorophyll content.

Gessner (18), Decker (17) and Went (35) are of the opinion that air flow causes an increase in photosynthesis. No attempt has been made to measure the rate of photosynthesis in this study. The increased air flow should increase photosynthesis if the plants are exposed to air flow for short duration. When the air flow continues for a long period the stomates tend to remain closed, thus preventing the entrance of CO₂ through stomata. This phase of the study with shade plants needs further investigation.

Results obtained in this study show that different species of plants behave differently under similar conditions of air flow. Saintpaulia ionantha and Philodendron cordatum made good growth and showed minimum signs of bleaching and burning lesions under 4.4 and 3.2 mph wind velocities, whereas other species gave good results at 0.45 mph wind velocity.

SUMMARY AND CONCLUSION

The leaf temperatures of all plant species in the morning (9:00 a.m.), noon and evening (4:00 p.m.) either under forced air movement or control were always higher than the corresponding air temperature. Although these differences varied with light intensity, rate of air flow and species.

Rate of air movement modifies the degree of increase in leaf temperatures. At wind velocities of 4.4 and 3.2 mph convection augmented by air currents and reradiation were perhaps major factors in cooling the leaves, whereas for the control treatment transpiration possibly was the major factor in reducing leaf temperatures. Cooling effects by forced air convection at 4.4 and 3.2 mph wind velocities were more efficient than by transpiration at control treatment.

Stomates of plants at 4.4 and 3.2 mph wind velocities remained closed, whereas at lower rates of air flow these remained open, thus facilitating transpiration.

Thick leaves of Saintpaulia ionantha and Sansevieria trifasciata acquired higher leaf temperatures compared to species having thinner leaves. Pubescent leaves and those with rough surfaces had higher leaf temperatures than the leaves having glossy or shiny surfaces.

Amount of chlorosis and burning lesions due to solarization was related to the rate of air flow, maximum being in control and minimum at 4.4 mph wind velocity. The degree of damage varied with species and temperature acquired.

Chlorophyll content was related to the rate of air flow. In Saintpaulia ionantha and Philodendron cordatum it increased with increase in

rate of air flow, whereas in other species it decreased with increase in wind velocity.

Pigmentation in leaves of Codiaeum auculifolium and Begonia semper-florens increased with increase in temperature which was related to the decrease in rate of air flow.

The amount of chlorophyll present was directly related to the rate of growth as measured in terms of plant height and general appearance.

Saintpaulia ionantha and Philodendron cordatum had larger leaves at higher wind velocities.

The overall growth pattern showed that species of shade plants behaved differently under similar conditions, especially with the rate of air flow. Saintpaulia ionantha and Philodendron cordatum made good growth at 4.4 and 3.2 mph wind velocities, whereas other species adapted well at 0.45 mph wind velocity. These differences might be due to different light intensity requirements and growth habits.

These observations show that there exists a relationship between light intensity and rate of air flow upon plant leaf temperature. Air flow modifies plant leaf temperature under high light intensities and thus prevents the shade plants from injury by solarization. This information can be useful in the commercial greenhouse production of shade plants.

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BIBLIOGRAPHY

1. Ansari, A. Q., and W. E. Loomis. 1959. Leaf temperatures. *Amer. J. Bot.* 47:713-717.
2. Böhning, R. H. 1949. Time course of photosynthesis in apple leaves exposed to continuous illumination. *Plant Physiol.* 24:222-240.
3. Böhning, R. H., and C. A. Burnside. 1956. The effect of light intensity on apparent photosynthesis in leaves of sun and shade plants. *Amer. J. Bot.* 43:557-561.
4. Boysen-Johnsen, P. 1932. *Die stoff produktion der elanzen.* Gustav Fischer verlag. ker, Jena.
5. Clum, H. H. 1925. The effect of transpiration and environmental factors on leaf temperature. I. Light intensity and the relation of transpiration to the thermal death point. *Amer. J. Bot.* 13:217-230.
6. Clum, H. H. 1926. The effect of transpiration and environmental factors on leaf temperature. I. Transpiration. *Amer. J. Bot.* 13:194-216.
7. Cook, G. D., J. R. Dixon, and A. C. Leopold. 1964. Transpiration: Its effect on plant leaf temperature. *Science.* 144:546-547.
8. Curtis, O. F., 1936. Leaf temperatures and cooling of leaves by radiation. *Plant Physiol.* 11:343-364.
9. Curtis, O. F., and O. Clark. 1950. *Introduction to plant physiology.* McGraw-Hill, New York. pp. 752.
10. Daubenmire, R. F., 1959. *Plants and environment.* John Wiley and Sons, New York. pp. 422.
11. Decker, J. P. 1947. The effect of air supply on apparent photosynthesis. *Plant Physiol.* 22:561-572.
12. Emerson, R. 1929. The relation between maximum rate of photosynthesis and concentration of chlorophyll. *J. Gen. Physiol.* 12:609-623.
13. Finell, H. H. 1928. Effect of wind on plant growth. *Agron. J.* 20:1206-10.
14. Fleischer, W. E. 1934. The relation between chlorophyll content and rate of photosynthesis. *J. Gen. Physiol.* 18:573-593.

15. Gates, David M. 1964. Leaf temperature and transpiration. *Agron. J.* 56:273-77.
16. Gates, David M., and Charles M. Benedict. 1963. Convection phenomenon from plants in still air. *Amer. J. Bot.* 50:563-573.
17. Gates, David M., E. C. Tibbals and Frank Kreith. 1965. Radiation and convection for Ponderosa Pine. *Amer. J. Bot.* 52:66-71.
18. Gessner, F. 1938. Die Beziehung Zwischen Lithintensitat und Assimilation bei Submersen Wasserpflanzen. *Jahrb. Wiss. Bot.* 86:491-526.
19. Georg, Hygen. 1954. The effect of wind on stomatal and cuticular transpiration. *Biol. Abstract*, 29(10):2456.
20. Konis, E. 1949. The resistance of Marquis wheat plants to supramaximal temperatures. *J. Ecology* 30:425-429.
21. Kuiper, P. J. C. 1963. The effect of environmental factors on the transpiration of leaves, with special reference to stomatal light response. *Biol. Abstract*. 41(5):2029.
22. Leopold, A. C. 1964. Plant growth and development. McGraw-Hill, New York. pp. 444.
23. Lorenz, R. W. 1931. High temperature tolerance of forest trees. *Minn. Agr. Expt. Sta. Tech. Bull.* 14:1-25.
24. Lubimenko, B. N., and E. R. Hubbenet. 1932. The influence of temperature on the rate of accumulation of chlorophyll in etiolated seedlings. *New Phytologist* 31:26-46.
25. MacKinney, G. 1941. Quantitative determination of chlorophyll a and b. *J. Biol. Chem.* 140:315.
26. Martin, C. V., and F. E. Clements. 1935. Studies of the effect of artificial wind on growth and transpiration of Helianthus annuus. *Plant Physiol.* 10:613-636.
27. Miller, E. C., and A. R. Saunder. 1923. Some observations on temperature of the leaves of crop plants. *J. Agr. Res.* 26:25-43.
28. Meyer, B. S., and D. B. Anderson. 1952. Plant physiology. D. Van Nostrand Co., Princeton, N. J. p. 200-201.

29. Rao, V. Panduranga. 1938. Effect of artificial wind on growth and transpiration in the Italian millet - Stearia italica. Bull. Torrey. Bot. Club. 65:229-232.
30. Raschka, K. 1961. Heat transfer between plant and environment. Ann. Rev. Plant Physiol. 11:11-126.
31. Sironval, C., and O. Kandler. 1958. Photo-oxidation processes in normal green chlorella cells. I. Bleaching process. Biochem. et Biophys. 29:359-368.
32. Wadsworth, R. M. 1959. An optimum wind speed for plant growth. Ann. of Botany. 23:195-199.
33. Wadsworth, R. M. 1960. The effect of artificial wind on the growth rate of plants in water culture. Ann. of Botany. 25:200-211.
34. Waggoner, P. E., and R. H. Shaw. 1951. Temperature of potato and tomato leaves. Plant Physiol. 27:710-724.
35. Went, F. W. 1957. The experimental control of plant growth. Chronica Botanica Co., Waltham, Mass. p. 336.
36. Withrow, A. P., and R. B. Withrow. 1949. Photoperiodic chlorosis in tomato. Plant Physiol. 24:657-668.
37. Whitehead, F. H. 1961. Experimental studies of the effect of wind on plant growth and anatomy. New Phytologist. 61:60-62.
38. Whitehead, F. H. 1962. Experimental studies of the effect of wind on plant growth and anatomy. III. Soil moisture relations (Helianthus annuus). New Phytologist. 62:80-85.
39. Walker, J. J., and A. D. Mellon. 1957. Light and heat in the bleaching of Chloroplastin euglena. Biochem. et Biophys. 25:267-274.
40. Wolpert, A. 1962. Heat transfer analysis of factors affecting plant temperatures. Significance of leaf hair. Plant Physiol. 37:113-120.
41. Wooley, J. L. 1960. Mechanism by which wind influences transpiration. Plant Physiol. 36:112-114.

RELATIONSHIP BETWEEN LIGHT INTENSITY AND VELOCITY OF AIR MOVEMENT
ON THE LEAF TEMPERATURES OF GREENHOUSE PLANTS

by

JAGDISH PRASAD NAUTIYAL

B. Sc. (Hons) Agr. Delhi University, 1954

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Plants differ widely in the intensity of light required or tolerated. Shade plants survive at lower light intensities because their light saturation point is much lower than those of sun species. Under conditions of high light intensities all phases of growth are retarded and plants suffer from insolation. High light intensity increases plant leaf temperatures which disrupts the physiological processes within the plant. Air movement moderates high leaf temperature by increasing leaf thermal emissivity.

The purpose of this investigation was to study the effect of different rates of air flow on leaf temperatures and growth of shade plants under high light intensity and further to explore the possibility of greater light intensity tolerance of these plants during greenhouse production by modifying plant leaf temperatures by means of increased air flow.

The experiment was conducted during the months of July and August, 1965. Five plants each of Saintpaulia ionantha, Philodendron cordatum, Begonia semperflorens, Codiaeum auculifolium and Sansevieria trifasciata were selected and double potted, the space between two pots was filled with peat moss to avoid rapid evaporation of water from the clay pot surface. A horizontal funnel-shaped plastic wind tunnel whose narrower end was two feet square and wider end eight feet square was constructed. An exhaust fan was installed at the narrower end and aspen-wood excelsior padding with facilities of wetting for humidification and cooling of air entering the tunnel. One plant of each species was placed on the horizontal wooden board in the tunnel at wind velocities of 4.4, 3.2, 0.6, 0.45 mph, and one plant was placed outside the tunnel to serve as control. Leaf temperatures at different wind speeds were measured weekly at 9:00 a.m. noon and

4:00 p.m. by means of 36 gauge copper-constantan thermocouple on a portable potentiometer. Light intensities were also measured by a Weston illumination meter, in conjunction with leaf temperatures. Observation notes on appearance and growth in relation to plant height and condition of stomates were also taken regularly. Leaves were analysed for chlorophyll contents after a 45 day period using a Beckman DU Spectrophotometer.

The results of this study revealed that leaf temperatures of all species and under all treatments in morning, noon, and 4:00 p.m. were higher than the corresponding air temperatures. Rates of air movement modified the degree of increase in leaf temperatures. Cooling effect by forced air convection at 4.4 and 3.2 mph velocities were more efficient than by transpiration for the control treatment. Stomates of plants at 4.4 and 3.2 mph wind velocities remained closed, whereas at lower rate of air flow these remained opened, thus facilitating transpiration. Thick leaves of Saintpaulia ionantha and Sansevieria trifasciata acquired higher leaf temperatures as compared to species having thinner leaves. Pubescent leaves and those with rough surface had higher leaf temperatures than the leaves having glossy or shiny surfaces. Amount of chlorosis and burning lesions due to solarisation was related to the rate of air flow and temperature of leaves. Maximum injury developed at the control treatment and minimum at 4.4 mph wind velocity.

Chlorophyll contents present were related to the rates of air flow. In Saintpaulia ionantha and Philodendron cordatum it increased with increase in air flow, whereas in other species it decreased with increase in wind velocity. The amount of chlorophyll was directly related to the rate of growth in terms of plant height and general appearance.

Saintpaulia ionantha and Philodendron cordatum had larger leaves at higher wind velocities, whereas the plant heights of other species decreased with increased air flow. Pigmentation, other than chlorophyll, in leaves of Codiaeum auculifolium and Begonia semperflorens increased with increase in leaf temperatures which was related to the decrease in the rate of air flow.

The difference in growth pattern exhibited by different species under similar conditions of air flow indicated that these plants differ in their light intensity and temperature requirements for growth. Saintpaulia ionantha and Philodendron cordatum made good growth at 4.4 mph wind velocity, whereas other species adapted well at 0.45 mph wind velocity.